





Physics Innovation in Spherical Torus Plasmas

Martin Peng

Oak Ridge National Laboratory on assignment at Princeton Plasma Physics Laboratory

Innovative Confinement Concept Workshop 2000

February 22-25, 2000 Berkeley, California, USA

Plan of Presentation



- Motivation
- What is a Spherical Torus (ST)?
- Innovative Physics Features
- Future Vision
- Conclusion

Tokamak Theory in Early 1980's Showed Maximum Stable β_T Increased with Lowered Aspect Ratio (A)



 A. Sykes et al. (1983); F. Troyon et al. (1984) on maximum stable toroidal beta β_T:

$$\beta_{Tmax} \approx \beta_N I_p / a B_T \approx 5 \beta_N \kappa / A q_j$$

where

 $\beta_N \sim \text{constant} \ (\sim 3 \ \%\text{m} \cdot \text{T/MA})$

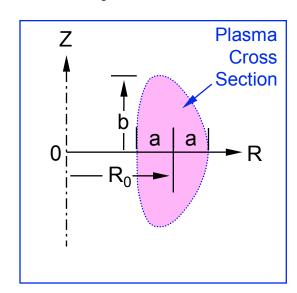
 κ = b/a = elongation

 $A = R_0/a = aspect ratio$

q_i ≈ edge safety factor

I_p = toroidal plasma current

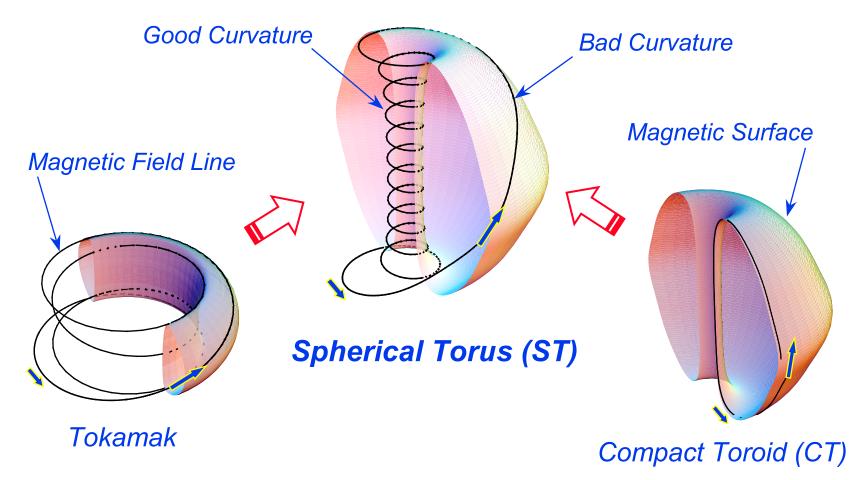
 $B_T \approx \text{applied toroidal field at } R_0$



- Peng & Strickler (1986): What would happen to tokamak as A → 1?
 - How would β_N , κ , $\mathbf{q_i}$, change as functions of \mathbf{A} ?

Minimizing Tokamak Aspect Ratio Maximizes Field Line Length in Good Curvature





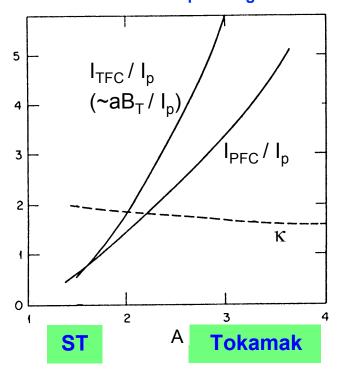
The outboard field lines are closer to CT.

Spherical Torus Plasma Elongates Naturally, Uses Less Coil Currents, and Increases I_p/aB_T & β_{Tmax}



Natural Elongation

Coil Currents/I_p (q_{edge}~2.5)

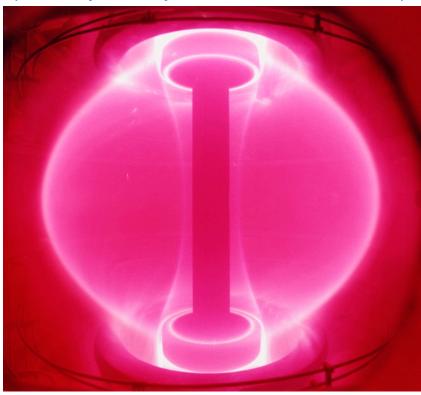


- Elongates naturally to κ ~ 2; I_{TFC} < I_p, I_{PFC} < I_p
- $I_p/aB_T \sim 7 \text{ MA/m} \cdot T \implies \beta_{Tmax} \sim 20\%$, if $\beta_N \sim 3$
 - Also, $I_p q_{edge} / aB_T \sim 20 \text{ MA/m} \cdot T \implies \text{strong "shaping"}$

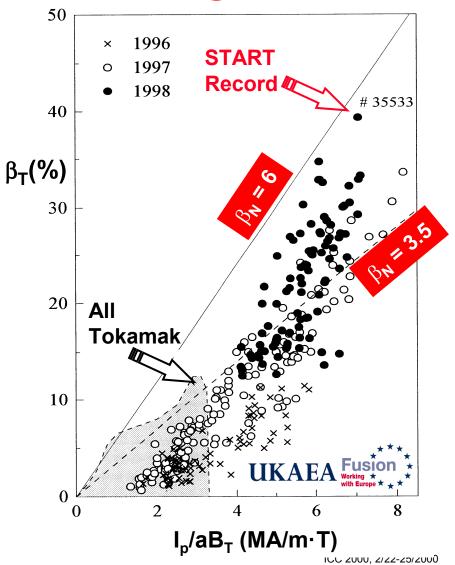
Record High β_T (~40%) was Achieved by START (U.K.) in 1998



(Courtesy of A. Sykes & START Team, U.K.)



- $I_p \sim 250 \text{ kA}$, $\langle \beta \rangle \rightarrow 15\%$, for $\sim 10 \text{ ms}$
- Low $q_{95} \sim 3$, $\kappa \sim 1.8$, no nearby wall
- β_N can be higher than 3

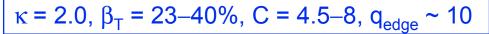


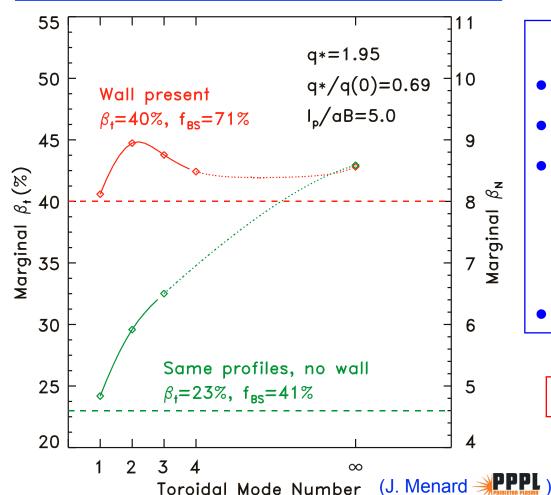
ST Introduces New Plasma Properties of Interest to Innovative Confinement Concepts

- Strong magnetic well (~30%), near-omnigenous orbits
 - Guiding-center orbit compression, reduced neoclassical transport?
 - Stability of "Fishbone" modes?
- Large Pfirsch-Schlüter current
 - Stabilization of neoclassical tearing modes at high β?
- $v_{sound} \sim v_{Alfvén}$, where local $\beta \sim 1$
 - "Dynamic" equilibrium with strong plasma flow?
 - Influence on stability and turbulence?
- $v_{fast} >> v_{Alfvén}$ for fast ions or fusion α particles
 - New classes of Toroidal Alfvén Eigenmodes, and effects?
- Larger ρ_i^* (= ρ_{ci}/a) ~ 0.03 0.01
 - Thicker pedestal in H-mode plasmas?
- Extreme low A (~1.1)
 - Connections to FRC and Spheromak?

NSTX Provides Opportunities Study Wall-Stabilized Beta Limits at $q \sim 10$ and $\kappa \sim 2$







Capabilities

- $R_0 = 0.85 \text{ m}$
- I_p ~ 1 MA
- Plasma heating
 NBI (5 MW)
 HHFW (6 MW)
 ECW/EBW (<1 MW)
- Plasma shape control

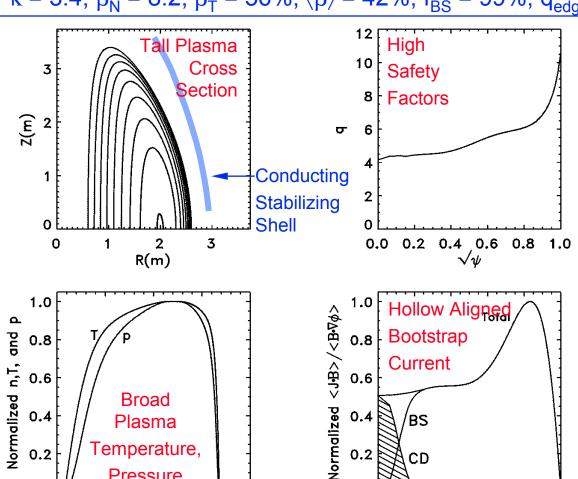
Stability at high q?

Recent Stability Calculations Suggest Route to **Self-Sustaining Higher** β **ST Plasmas**

0.0 0.2 0.4 0.6 0.8 1.0







Pressure

1.8

R(m)

2.4

3.0

1.1

0.5

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Challenges

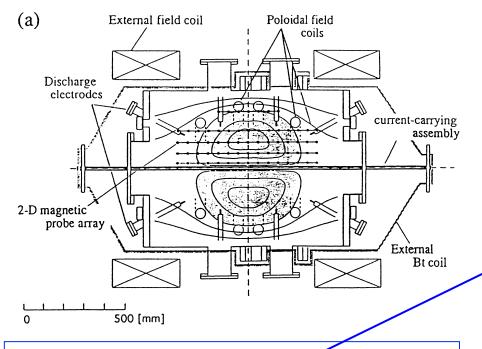
- Vertical stability
- **Disruptions**
- **Resistive Wall** Mode stability & control
- Neoclassical tearing mode stability
- Profile tailoring
- Bootstrap current alignment

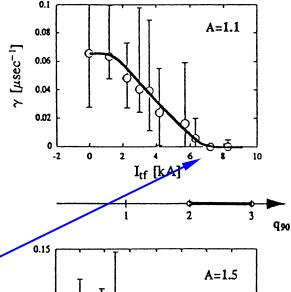
(J. Menard, PLASTICETOR PLASTI

Can FRC & Spheromak Tilt Be Stabilized by Applying B_T? Opportunity: Add B_T to RFC in TS-3

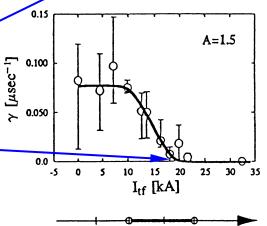
(Y. Ono, Japan)







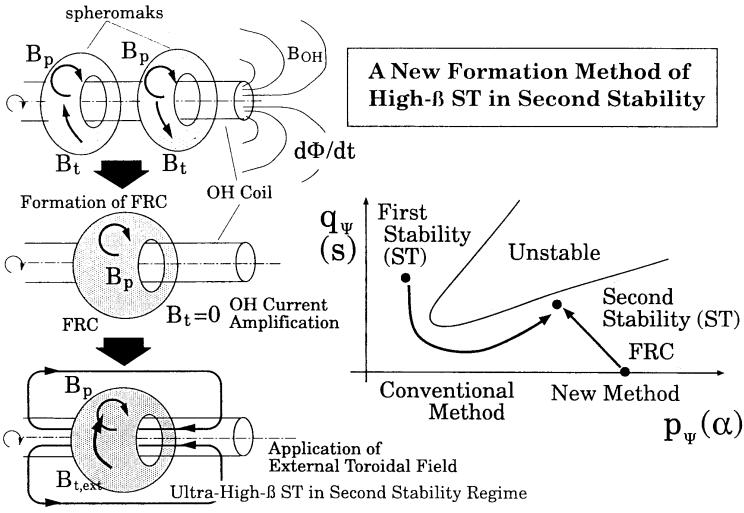
- FRC in TS-3 tilt stabilized when safety factor q₉₀ reaches ~3
- Merged Spheromaks → heated FRC → High-β diamagnetic ST (β_T ~ 70%)
- A ~ 1.1 → much reduced I_{TF} → power plant economy



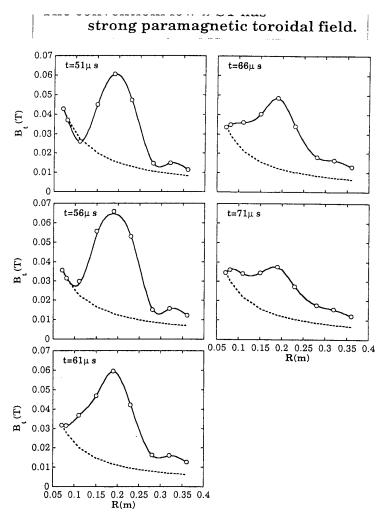
ICC 2000, 2/22-25/2000

Can FRC & Spheromak with Small B_T Provide Very High Stable Beta? (TS-3, Y. Ono, Japan)

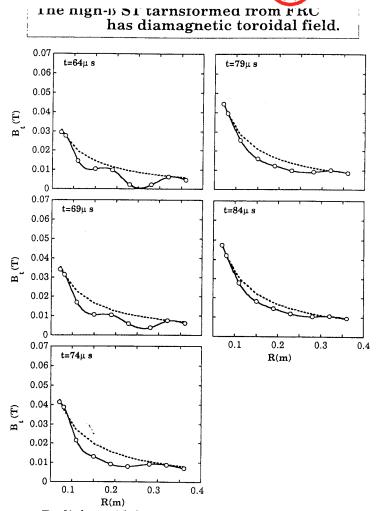




Can FRC & Spheromak with Small B_T Provide Very High Stable Beta? (TS-3, Y. Ono, Japan)



Radial toroidal magnetic field profiles of ST formed conventionally



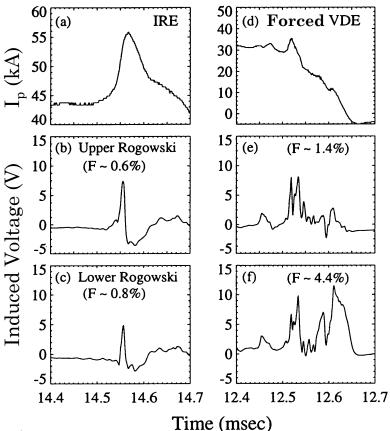
Radial toroidal magnetic field profiles of high-ß ST transformed from FRC

Spherical Torus May See Only Modest Impact of Disruption-Induced Halo Currents

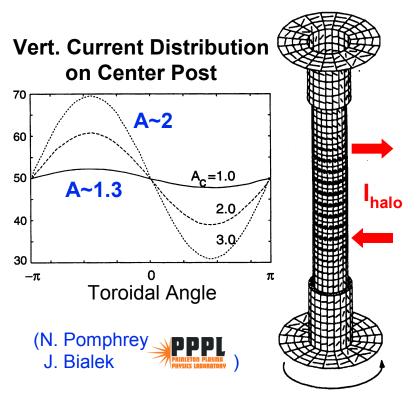


 CDX-U and START measured modest I_{halo} fraction (F < 5%) during disruption-like events

(Courtesy of M. Ono and CDX-U Team)



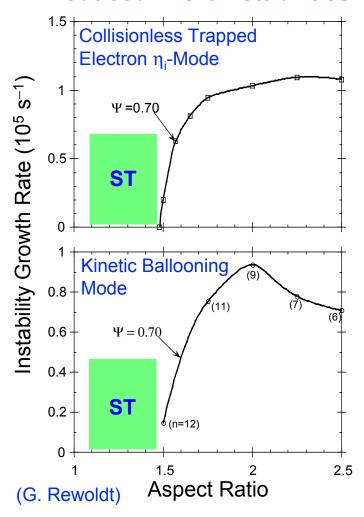
- Eddy current simulation indicates strong symmetrization at low A
- ⇒ Reduced forces



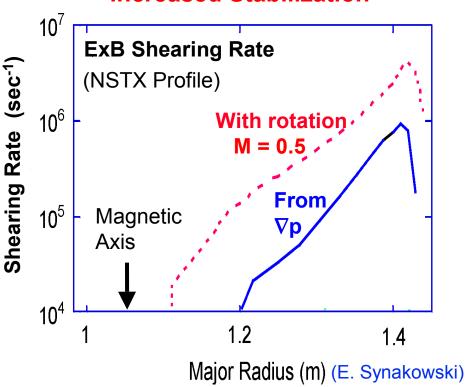
Turbulence May Be Much Reduced in NSTX



Reduced Microinstabilities



Increased Stabilization



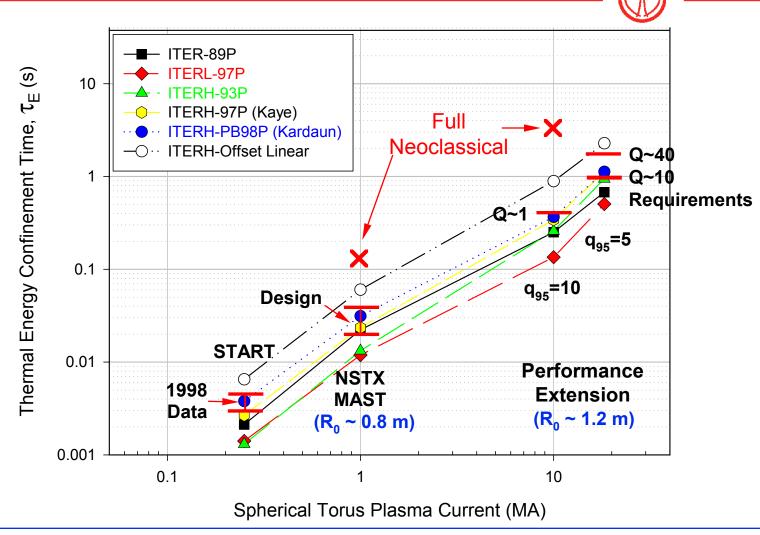
• Opportunity: Flow shearing rates >> microinstability growth rates



Challenge: Is reduced turbulence compatible with stable high β?



Enhanced Confinement in NSTX Projects to High Performance Performance Extension Test



ST experiments also improves fundamental understanding of plasma transport.

ST Phys Innovations

Coaxial Helicity Injection (CHI) Draws on CT Research for Noninductive Current Drive in ST

Toroidal Insulator

TF Coil

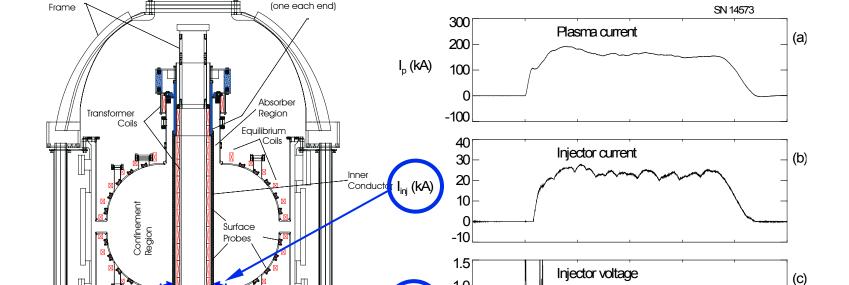
Tapered Injector

Region

1 meter



(Courtesy of T. Jarboe, UW)



1.0 0.5

-0.5

0

Benefit: Eliminate the solenoid, simplify design **Opportunity**: Scale up test in NSTX at ~0.5 MA

2

Time (ms)

6

8

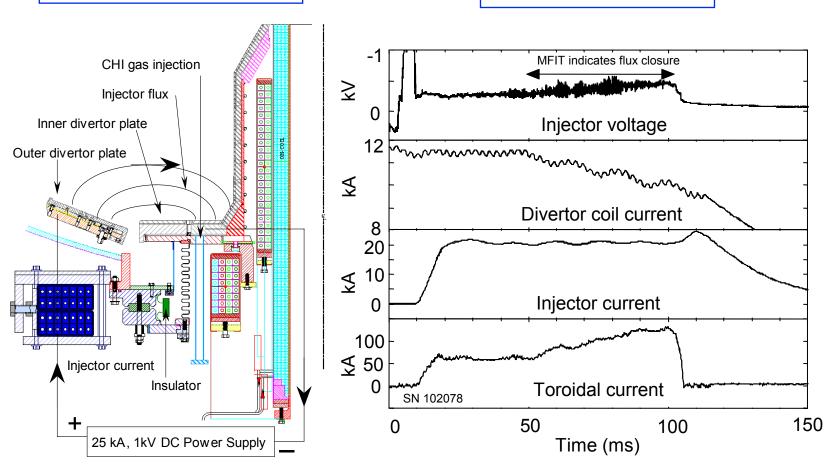
10

Initial Tests of CHI on NSTX Has Been Successful



Injector Region Design

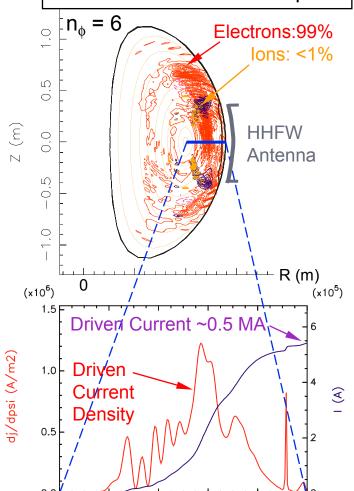
Best Results So Far



High Harmonic Fast Wave Utilizes High ϵ (~100) in ST for Efficient Heating & Current Drive







0.6

rho

0.2

M. Ono (1995): Fast wave decay (absorption) rate:

$$k_{\perp im} \sim n_e / B^3 \sim \epsilon / B$$
,

$$\varepsilon = \omega_{\rm pe}^2 / \omega_{\rm ce}^2 \sim 10^2$$



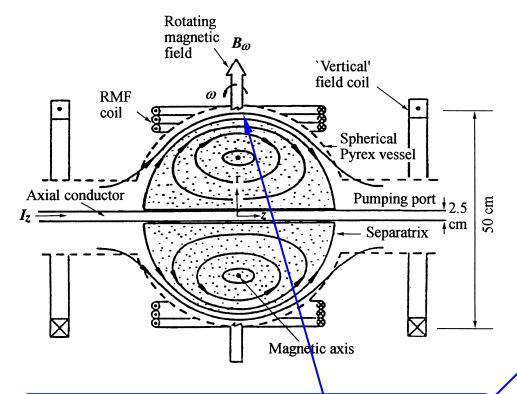


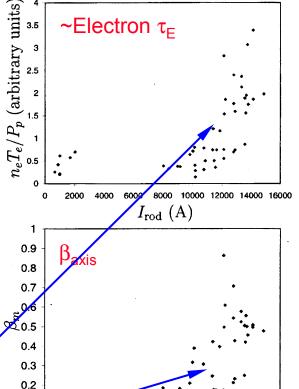
12 HHFW ANTENNA

(PICES & RANT codes, F. Jaeger & M. Carter OTTL)

Challenge: Relationship between FRC and ST? Opportunity: Put I_{rod} in Rotamak (leuan Jones, Aus.)







8000

 $I_{\rm rod}$ (A)

12000

ST

16000

~Electron τ_E

- Rotamak uses transverse rotating magnet field to induce electron slippage current,
- FRC evolves to ST by increasing I_{rod}
- Some improvements in β and τ_F

ICC 2000, 2/22-25/2000 ST Phys Innovations

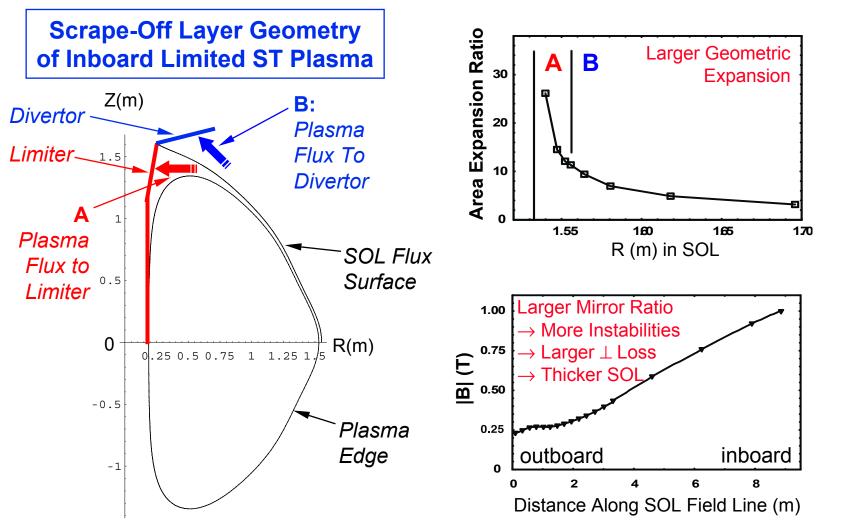
0.1

4000

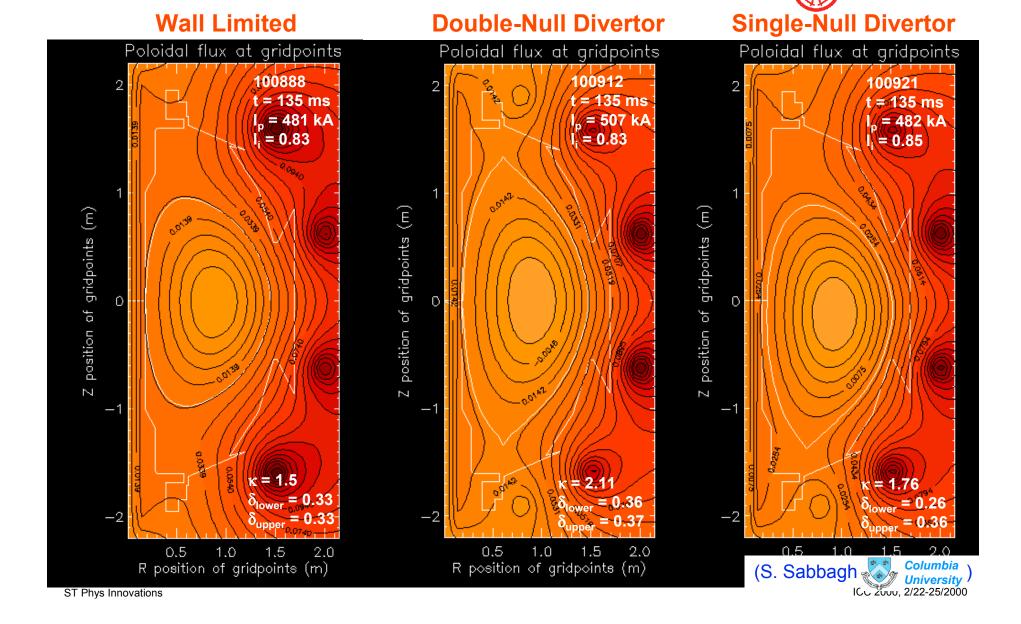
FRC

Heat Fluxes Can Be Dispersed Over Large Wall Areas





Various Plasma Shapes Have Been Produced in NSTX, Also Needed for SOL Investigations



Spherical Torus Introduces Both Exciting Fusion Science and a Possible Practical Route to Energy



Promise: SCIENCE ↔ **ENERGY**

High Pressure, Low Field

Suppressed Turbulence

Dispersed Exhaust

Startup Without Solenoid

→ Small Unit Size

→ Reliable First Wall

→ Simplified Compact Configuration

New Challenge: SCIENCE, TECHNOLOGY

Startup Without Solenoid

→ Noninductive Startup Physics

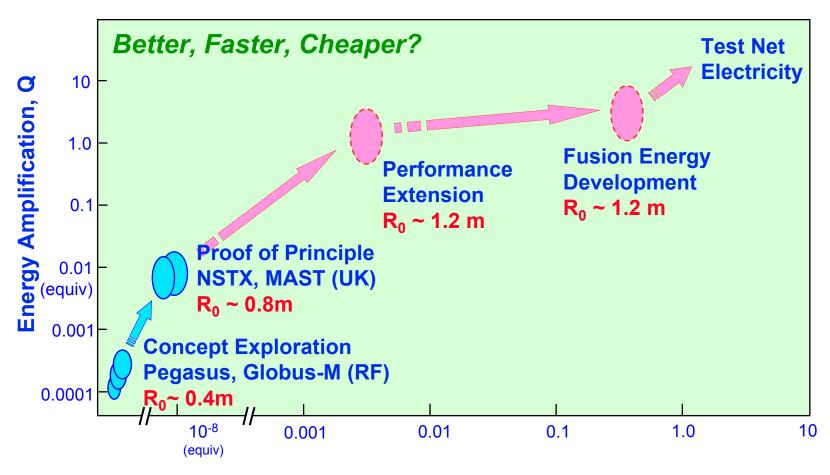
Single-Turn Center Conductor

Recirculating Power, Lifetime

ICC 2000, 2/22-25/2000 ST Phys Innovations

ST Development Path for Fusion Energy and Technology May Be More Affordable





Average Neutron Load (MW-a/m² per Year)

Spherical Torus Plasmas Offer Innovative Physics Opportunities



- Derived from Tokamak and Compact Toroid research
- Offers exciting scientific opportunities and challenges for fusion
 - Order-unity β
 - Good confinement
 - Self-sustained current
 - Dispersed heat fluxes
 - Full noninductive startup
- Introduces new physics features to be explored in relationship with FRC and Spheromak
- May offer affordable steps to advance fusion energy science
- NSTX, Pegasus, HIT-II, CDX-U in the U.S., together with ST experiments around the world, are ready to address key issues